The Metamorphic Underwater Vehicle (MUV) is a vehicle that propels in the water by continuously changing the shape of its body similar to the motion of the microorganism amoebae. In this article, we describe the basic design of Amoebot, a plastic MUV that achieves shape-changing capability through the inflation and deflation of water-filled balloons. A sequence of inflation and deflation procedures can be taken to produce cyclic swimming shapes that propel the MUV. Swimming shapes similar to the microorganism amoebae have been successfully reproduced by present Amoebot. The mechanical system designed proves to be very reliable and flexible in producing desired body shapes. The physical shape of the Amoebot is analyzed numerically and its variation in time during the swim can be expressed explicitly. By formulating sets of idealized swimming rules based on the changing shape, simulations are carried out to predict the trajectory and study the pseudo dynamics of the swimming of Amoebot. Possible applications of this type of underwater vehicle are discussed.

1. INTRODUCTION

Modern vessels traveling on or under the water surface use propellers for propulsion and rudders for controlling the direction of travel. The propulsion force is generated due to the pressure difference between the two sides of the rotating propeller. This kind of propulsion system will generate a significant amount of noise, thus making the vessel lose the advantage of stealth and also making it unfriendly to marine ecology and environment. Quite contrarily, marine mammals and microorganisms usually propel in the water through continuous change of the body. Such propulsive principle is developed by creatures naturally and is extremely energy efficient.

In this article, we describe a project aimed at developing a propeller-less biologically inspired underwater vehicle.
water vehicle system, *Amoebot*, as an alternative to the existing submersible systems. The Amoebot is a Metamorphic Underwater Vehicle (MUV) whose locomotion is inspired by the self-propulsion of the microorganism. The microorganism can propel itself in very low Reynolds number flow through the shape change of its body. Similarly, through the change of the body shape, the MUV can swim silently and has the capability to pass regions with obstacles under the water. The locomotion principle based on the geometrical shape change will be discussed in Section 2. The prototype design of Amoebot that can swim in 2D space will be covered in Section 3. The geometric shape control through the Programmable Logic Controller (PLC) will be described in Section 4. Experiment result is discussed in Section 5. Idealized swimming rules are formulated in Section 6. This article is concluded with a summary and discussion on the possible application in Section 7.

2. LOCOMOTION PRINCIPLE OF AMOEBAE

The unique feature of amoebae’s swimming locomotion is the absence of the inertia. Fluid dynamics in this situation is characterized by low values of Reynolds number, which is the ratio of the inertia over viscosity. Similar to an ant crawling around randomly with its slender legs while struggling on the surface of a raindrop, an amoebae squeezes, twists, and rotates its body in order to move in a very thick and viscous fluid world. This locomotion has been formulated mathematically and studied systematically.\(^1\)\(^-\)\(^3\) It is found that the motion is completely determined by the geometry of the sequence of shapes the swimmer assumes in a two-dimensional space. The self-propulsion comes from slowly changing the body from one shape to another. Moreover, accompanying the forward movement, the body rotates slightly each time it goes through a translation under this formulation. This results in an interesting trajectory that returns to its starting point eventually.

3. MUV DESIGN

The geometric shape of the real amoebae can be considered as a distorted sphere so that the microorganism is capable of generating motion in 3D space. To validate the locomotion principle, we use a simplified design so that the shape of the MUV will have planar deformation and the vehicle will produce 2D planar motion. The basic MUV system consists of three main parts: the core structure, the shape changing mechanism, and the control system. Detailed description of the system is covered in ref. 4.

3.1. Core Structure

The core structure of a 2D MUV is designed to be a flat hollow cylinder as shown in Figure 1. The top and bottom faces of the cylinder are made of circular Perspex plates for ease of observation. The diameter and the height of the cylinder are 220 and 90 mm, respectively. Eight open chambers are divided by rigid walls between the two plates and are located along the circumference of the cylinder. The chambers will host the inflatable balloons to provide the ability to change the shape of the body. Teflon panels are inserted in between the walls to be able to slide in and out in the radial direction. The sliding panels can function as the extension of the balloon chamber and the support for the elastic “skin” that covers the entire vehicle. The chamber design follows modularity principle. As shown in Figure 1, the current MUV design has eight chambers. The number of the chambers can be increased by repartition of the circular cylinder. In this case, more balloons can be mounted to the vehicle and more complicated shapes can be generated.

3.2. Shape Changing Mechanism

Various shape-changing mechanisms have been evaluated. The basic consideration in designing the mechanism is to maintain minimum shift of the center of gravity of the vehicle while the vehicle body deforms. Water-inflated balloons are chosen as the final design because they can remain neutrally buoyant all the time. Furthermore, this design can avoid the waterproof problem since the interior and the exterior of
the vehicle are of the same type of the fluid. The balloons are made of elastic material, such as latex. The inlet of the balloon is attached to the tubing fixed on the inner wall of the chamber. The other end of the tube is attached to a two-way fluidic valve for the inflation and deflation of the balloon. As the size of the inflated balloon exceeds the size of the chamber, the balloon will expand beyond the chamber in the core structure. The elastic skin wrapped around the entire MUV will then stretch until the tension of the skin is balanced with the internal pressure of the inflated balloon. The sliding panel will guide the direction of expansion and provide the necessary support to the expanded balloon.

3.3. Control System

Because the MUV will generate both translation and rotation motion in the 2D space, spatial orientation control can be avoided. The effect of gravity can be neglected as we can mount additional balloons in the direction perpendicular to the flat cylinder to provide enough buoyancy to neutralize the gravity.

The major concern in controlling this MUV is the geometric shape of the vehicle so that necessary 2D planar motion can be produced. Hydraulic control systems are employed here due to the use of water-filled balloons. The control system of the MUV consists of a fluidics pump, eight two-way valves to control the water into and out of the balloons, and a programmable logic controller as shown in Figures 2 and 3. The filling sequences of the balloons are controlled by the PLC. Different sequences can be programmed into the PLC to change the course of the MUV. Because of the space constraint, all the fluidic control circuits, including the pump, the valves and the tubing, are mounted on a fixture outside the vehicle. Note that all control devices are off-the-shelf components for ease of implementation. Minimal effort in controlling and interfacing the valves is needed due to the use of the PLC.

4. CONTROL OF THE GEOMETRIC SHAPE

At current stage, we would like to investigate how the geometric shape change will affect the movement of the vehicle. Precise control of the shape for steering the vehicle actively is not necessary. Therefore, an open loop control of the geometric shape of the vehicle satisfies our objective. The shape control is accomplished through the filling sequences of the balloons. The sequences can be programmed into the PLC. Two types of filling sequences are required: the initialization sequence and the swimming sequence.

The initialization sequence is used to initiate the shape changing action by filling the balloons with water. Initially, water will be pumped to all eight balloons and then allowed to circulate for a long time to purge all the air out of the system. Then, balloons will be half filled so the MUV will be able to maintain a circular shape before the start of the next sequence. The initialization sequence will be used only once when the MUV is turned on.

The swimming sequence is used after the initialization sequence is completed. This sequence will produce the desired continuous deformation of the shape. The swimming sequence will be used repeatedly until a stop command is issued from the controller. Figure 4 shows the actual and graphical shape-changing stages of one swimming sequence. Detailed description of the sequences is discussed in ref. 4. The shape sequence has an axis of symmetry (called a principal axis) as indicated in the figure. The production of this shape sequence is through trial and error at this moment. The purpose of this shape sequence is to move Ameobot along its principal axis in a straight line. Hence, water in the eight balloons is moving back and forth in symmetric fashion to keep the total volume of water constant.
5. EXPERIMENTAL RESULT

Preliminary experiments have been carried out to establish the performance of each individual component. The MUV can actually stay neutrally buoyant with minimum vertical movement during the experiment. The prescribed shapes derived from the locomotion principle can be produced with the balloon-based shape changing mechanism (Figure 4). The MUV has been allowed to run for many cycles of shape sequence to establish the repeatability of the mechanism. The volume of one fully filled balloon is about 1 l and it will take about 30 s to reach this stage. The initialization sequence will take about 60 s. A complete cycle of shape sequence for swimming will take about 2 min. Changing the setting time between the shape sequences can alter the timing of the complete cycle of shape sequence. The inflation and deflation rates of the balloons are kept slow in order to emulate the low Reynolds number world of the amoebae.

Figure 5 illustrates the experimental setup for capturing the actual trajectory of the robot while executing the swimming sequence. The robot was kept neutrally buoyant so as to move on a horizontal plane only. A digital video camera was mounted above the robot with a fixed distance. A reference grid was laid down on the floor of the water tank as reference for the movement of Ameobot. The movement of Ameobot was captured through the digital video camera and analyzed every 5 s. The trajectory of the center of Ameobot was plotted in Figure 6 based on the swimming sequence illustrated in Figure 4. In the experiment, the principal axis of Ameobot is initially
aligned with the x-axis of the graph. During the shape change phases, irregular movement of Ameobot was observed and was indicated in the irregular trajectory of the center of the robot. The irregularity may be due to the difference of the inflation rate of each balloon that needs further investigation. However, after completing one cycle of shape sequence, the robot indeed created a net displacement of 1.4 mm along the x-axis (or the principal axis of the robot) approximately. This experiment can preliminarily show that the Ameobot can use its shape mechanism for underwater locomotion.

6. SWIMMING RULES AND TRAJECTORY SIMULATION

Even if the swimming locomotion of amoebae is being followed closely, one cannot expect the MUV to undergo similar trajectory. The physical size and weight and the rigid internal structure of the MUV make the formulation of the swimming rules of amoebae based on vanishing Reynolds number invalid. Therefore, a new set of swimming rules has to be established before the trajectory can be predicted and compared with the experimental results. Based on the design of Ameobot, shape produced by the inflation of balloons can be expressed mathematically in terms of the degree of inflation of each balloon. Then, given a sequence of driving shapes and a set of swimming rules, the trajectory of Ameobot can be simulated and analyzed.

6.1. Shape of Ameobot

The geometric shape of the MUV projected on a plane forms an area defined by a closed curve that can be considered as a distorted circle. Without loss of generality, this closed curve can be described in a local coordinate frame fixed to the core of MUV. Because the core is a cylindrical structure, the origin of the local coordinate frame can be chosen at the center of the cylinder, termed the geometric center C_g as shown in Figure 7. At any instance t, the shape of the robot can be described as S^* (r, θ, t), where θ is the angle measuring from the x-axis of the body frame. Since the shape is controlled by the inflation of the balloons, we can determine S^* as a function of the degree of inflation of the balloons or approximate S^* by curve fitting through the farthest points on the balloons.

In the current design, the MUV has eight independently inflatable balloons, which provide eight independent inputs. Let the distance of the farthest point on balloon i to the geometric center C_g be r_i, which can be controlled by the fluidics control system. All balloons are equally spaced around a circle at 45°. The eight necessary conditions to be satisfied for curve fitting purpose are r(0, t) = r_0, r(π/4, t) = r_1, r(π/2, t) = r_2, ..., r(7π/4, t) = r_7. Cubic spline functions can be used for the curve fitting of a C^2 smooth contour curve r(θ, t) for the body shape. The total area A of the geometric shape can be determined by

\[ A(t) = \int_0^{2\pi} \int_0^{r(\theta, t)} r' d r' d \theta. \]  
(1)

The surface length L, the hydraulic radius R = A/L, the moment of inertia I, and the center of mass C_m can be calculated in similar fashion with respect to the shape S^* (r, θ, t) as well.

6.2. Swimming Action

Suppose the geometric center C_g of the MUV is located at x_g with respect to a fixed world reference frame. The shape of the MUV can be described in the world frame through a planar rigid transformation and denoted as S(t, x_g(t)). To compare with experimental trajectory and study the dynamics of the MUV swimming, numerical simulation of the swimming based on S(t, x_g(t)) can be performed if the swimming rules are known.

Strictly speaking, a direct computation of the resultant forces acting on the MUV swimming in a viscous fluid will be the most reliable approach to predict the trajectory without making any assumption on the swimming rules. Given the time sequence of the shape S(t, x_g(t)), the induced flow field and pressure field around the surface of the MUV can be calculated directly. The instantaneous linear and
angular acceleration can then be integrated to give the trajectory. However, each simulation result will depend sensitively on the initial conditions and deriving a general swimming mechanism out of simulations will be extremely time consuming and tedious. The difficulties associated with the direct simulation of a shape-changing body swimming interactively in a viscous fluid make this approach even more challenging.

To facilitate the study of Amoebot trajectory, a general model of an idealized swimming mechanism has to be formulated. Classical dynamical theory on the motion of rigid body through infinite inviscid fluid has been formulated by Lamb. Following the spirit and formulation based on an impulsive movement, simple robust swimming rules for a real robot in viscous fluid can be derived.

Considering a small mass $\delta m$ within the Amoebot, the impulsive change of shape from $S(t,x)$ to $S(t+\Delta t,x)$ will generate an instantaneous velocity $v$. This process can be considered as a conversion from internal bio-energy to kinetic energy $\delta m v^2/2$. Integrating over the entire mass, the total kinetic energy of the system can be given as $m V^2/2$, where $m$ is the mass of Amoebot and $V$ is the averaged velocity of the center of mass $C_m$. Suppose $C_m$ is located at $x_m$. Having the position change of $C_m$ (see Figure 8) as $\Delta x_m = x_m(t+\Delta t) - x_m(t)$, then $V = \Delta x_m / \Delta t$. From the energy point of view, this impulsive motion will be stopped as Amoebot moves through the viscous fluid over a certain length. The viscous dissipation can be written in terms of the surface shear stress, total surface area, and the traveling distance. Similarly, the rotational motion of Amoebot can be formulated based on this energy argument. Having $\Delta t$ goes to zero, the resulting rules of swimming are given as

$$\dot{x}_m(t) = \sqrt{\gamma} \dot{x}_m,$$  (2)

where $\dot{x} = dx/dt$, and $\gamma$ is the specific weight of Amoebot. The time is scaled by a viscous diffusive time $R^2/\nu$, and $\nu$ is the viscosity of the fluid. Eqs. (2) and (3) also imply a transformation from the body coordinate frame to the world coordinate frame (Figure 9). This robot follows closely the swimming spirit of Amoebae, which travels by squeezing suddenly its body mass towards the direction of motion and relaxing slowly back to its original mass distribution. Due to the nature of the swimming mechanism, this set of rules can be termed the energy rule.

Consider the same impulsive shape change discussed above. When Amoebot pushes its surface into the surrounding fluid, another set of rules can be derived based on the surface pressure. For a small surface area $r(\theta,t)d\theta$ (Figure 10), the mass flow rate due to the pushing of the surface from $r(\theta,t)$ to $r(\theta,t+\Delta t)$ can be expressed as $\rho r(\theta,t)d\theta [r(\theta,t+\Delta t) - r(\theta,t)]/\Delta t$. Then, the force acting on the surface when Amoebot pushes the fluid at velocity $[r(\theta,t+\Delta t) - r(\theta,t)]/\Delta t$ can be given as

$$\dot{\theta}(t) = \frac{1}{2} \sqrt{\frac{\gamma}{AR^2}} \frac{\dot{x}_m \times \dot{x}_m}{|\dot{x}_m|^2},$$  (3)

where $\dot{x} = dx/dt$, and $\gamma$ is the specific weight of Amoebot. The time is scaled by a viscous diffusive time $R^2/\nu$, and $\nu$ is the viscosity of the fluid. Eqs. (2) and (3) also imply a transformation from the body coordinate frame to the world coordinate frame (Figure 9). This robot follows closely the swimming spirit of Amoebae, which travels by squeezing suddenly its body mass towards the direction of motion and relaxing slowly back to its original mass distribution. Due to the nature of the swimming mechanism, this set of rules can be termed the energy rule.

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Other than neglecting the resultant flow field due to the pushing of the surface, this swimming rule actually models the swimming mechanism of real-life animals, which paddles fluid to the back in order to swim forward. Due to the nature of the swimming mechanism, this set of rules can be called the momentum rule.

6.3. Trajectories

Trajectories based on each of the above rules have been obtained by integrating the translation and rotation equations in time from a set of initial conditions. The swimming is driven by having Amoebot squeeze its mass suddenly towards the desired direction of travel and to relax back to its original distribution slowly. The eight corresponding conditions at balloons are

\[ r(0,t) = 1 - 0.1 \sin \varepsilon, \quad r(\pi/4,t) = 1 - 0.1 \sin \varepsilon, \]
\[ r(\pi/2,t) = 1 + 0.3 \sin \varepsilon, \quad r(3\pi/4,t) = 1 + 0.3 \sin \varepsilon, \]
\[ r(4\pi/4,t) = 1 - 0.1 \sin \varepsilon, \quad r(5\pi/4,t) = 1 - 0.1 \sin \varepsilon, \]
\[ r(6\pi/4,t) = 1 - 0.1 \sin \varepsilon, \quad r(7\pi/4,t) = 1 - 0.1 \sin \varepsilon, \]

where \( \varepsilon \) is a nonlinear driving time given as

\[ \varepsilon = \frac{\pi}{2} \frac{t'}{0.1} \quad \text{when} \quad 0 \leq t' \leq 0.1, \]
\[ \varepsilon = \frac{\pi}{2} \frac{t' - 0.1}{0.9} \quad \text{when} \quad 0.1 \leq t' \leq 1.0, \]

and \( t' = t - [t] \) with \([t]\) the Gaussian integer. The set of functions drives Amoebot towards a direction between the north and northwest. Using the cubic spline curve fitting, the shape sequence according to the driving functions is shown in Figure 11. The shapes of Amoebot return to its initial geometry after \( t \) goes from 0 to 1. A new cycle will start when \( t > 1 \).

The simulated trajectory of Amoebot based on the energy rule is shown in Figure 12, which describes a forward–backward movement in a straight line with minimal body rotation. The specific weight \( \gamma = 100 \). The scaled time \( t \) is from 0 to 1. Initially, the body coordinate frame of the robot is coincident with the world frame. Based on the proposed drive, the duration for the retracting phase is four times of that of the stretching phase. In this case, they are 0.8 and 0.2, respectively. The robot will then follow the fast stretching action forward, and then return slowly because of the slow retraction action. After one complete stretching and retracting cycle, the center of geometry \( C_g \) moves from \((0, 0)\) to \((-0.0833, 0.1982)\), a net traveling distance of 0.1 body length approximately. In the meantime, the body rotates 0.0860° in the clockwise direction.

The simulated trajectory of Amoebot based on the momentum rule is shown in Figure 13. Within the
same time period \([0, 1]\) under the same driving sequence, \(C_s\) moves from \((0, 0)\) to \((0.0705, -0.1680)\), a net traveling distance of 0.09 body length approximately. In the meantime, the body maintains its orientation, i.e., \(\theta = 0^\circ\). Because the robot stretches in the northwest direction and retracts in other directions symmetrically, the reaction force exerted by the surrounding water will make the robot move in the direction opposite to the one produced by the energy rule. The backward acceleration due to the slow retracting is insignificant compared with the net velocity at the end of the strong forward motion.

7. SUMMARY

We have described a vehicle that propels itself in the water using the geometric shape change of the body according to the microorganism. The shape changing capability is through the use of several water-inflated balloons mounted on the vehicle. The shape control is accomplished by using fluidic valves and the PLC to generate inflation and deflation sequences of the balloons. The initial experiment has shown the feasibility of utilizing this type of mechanism for shape changing purpose. More experiments will be carried out to verify and characterize the movement of the MUV. Based on idealized swimming rules, the energy rule, and the momentum rule, the trajectory of the vehicle has been formulated mathematically in terms of the body shapes to allow numerical simulations. The movement of the MUV will follow more closely with the momentum rule, which is described by a set of nonlinear differential integral equations. On the other hand, we believe that the locomotion of amoebae in very low Reynolds number flow can be approximated by the energy rule.

In the context of the momentum rule, the interaction between the two-dimensional robot and the fluid has been formulated into a dynamical system. This allows us to systematically study the swimming under various driving sequences. The trajectories produced will be analyzed to shed lights on position control and path planning of Amoebot. Since the simulated trajectory of the dynamical system is sensitive to its initial conditions, a comprehensive study of the nonlinear behavior is underway.

Presently, we are exploring other potential applications of this MUV. Considering an MUV falling vertically under the gravity, the maneuverability of the MUV through its shape changing mechanism can make it remain at a desired location within a flow. This ability makes it an attractive tool for underwater positioning or deployment.

REFERENCES